

Colloid Microthruster Flight Performance Results from Space Technology 7 Disturbance Reduction System

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The Space Technology 7 Disturbance Reduction System (ST7-DRS) is a NASA technology demonstration payload as part of the ESA LISA Pathfinder (LPF) mission, which launched on December 3, 2015. The ST7-DRS payload includes colloid microthrusters as part of a drag-free dynamic control system (DCS) hosted on an integrated avionics unit (IAU) with spacecraft attitude and test mass position provided by the LPF spacecraft computer and a gravitational reference sensor (GRS) as part of the LISA Technology Package (LTP). The objective of the DRS was to validate two technologies: colloid micro-Newton thrusters (CMNT) to provide low-noise control capability of the spacecraft, and drag-free flight control. The CMNT were developed by Busek Co., Inc., in a partnership with NASA Jet Propulsion Laboratory (JPL), and the DCS algorithms and flight software were developed at NASA Goddard Space Flight Center (GSFC). ST7-DRS demonstrated drag-free operation with less than 10nm/√Hz level precision spacecraft position control along the primary axis of the LTP using eight CMNTs that provided 5-30 μN each with ≤0.1 μN precision. The DCS and CMNTs performed as required and as expected from ground test results, meeting all Level 1 requirements based on on-orbit data and analysis. DRS microthrusters operated for more than 2400 hours in flight during commissioning activities, a 90-day experiment and the extended mission. This mission represents the first validated demonstration of electrospray thrusters in space, providing precision spacecraft control and drag-free operation in a flight environment with applications to future gravitational wave observatories like the Laser Interferometer Space Antenna (LISA).

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I. Introduction

The Space Technology 7 Disturbance Reduction System (ST7-DRS) was developed to demonstrate the technologies required for nanometer spacecraft position control and ‘drag-free’ operation capability for future missions. The primary application is a gravitational wave observatory like the recently selected Laser Interferometer Space Antenna (LISA) for ESA’s L3 flagship mission, intended for launch in 2034. Precision spacecraft control is also of interest as a distinct technology area, for use with separated-spacecraft interferometry, formation flying, and precision pointing for the next generation of space telescopes. DRS was originally selected by NASA’s New Millenium Program, and has been supported by the Astronomy and Astrophysics Directorate and Physics of the Cosmos Program. ST7-DRS was hosted as a payload on the ESA LISA Pathfinder (LPF) spacecraft. Launched in December 2015, it was the first validated demonstration of electrospray thruster technology in flight.

The mission profile is illustrated in Figure 1. Commissioning operations were conducted in January 2016 to check the functionality of the DRS subsystems, including the microthrusters [1]. LPF arrived on station at Earth-Sun L1 Lagrange point on January 22. ESA LISA Technology Package (LTP) executed its primary mission first [2,3]. The DRS primary mission operations were conducted during June - December 2016. Extended mission operations were conducted during several weeks from January through April 2017 with additional experiments, further characterizing the performance and capabilities of the DRS and the DRS sub-systems.

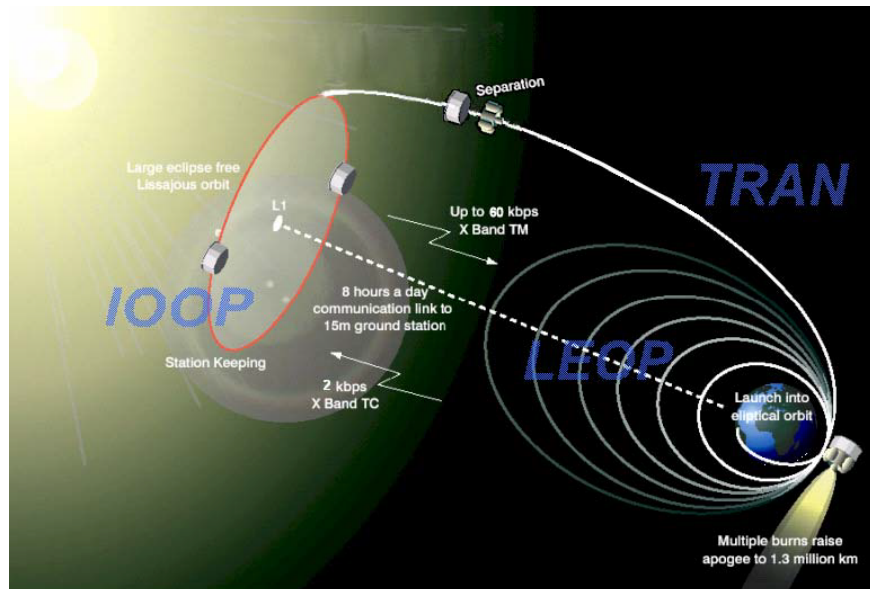


Figure 1. LISA Pathfinder and DRS Mission Profile.

The DRS consisted of four major subsystems to achieve spacecraft attitude control, drag-free operations and nanometer spacecraft position control using the gravitational reference sensor (GRS) on the LTP. It included the colloid micronewton thrusters (CMNT) [4], Dynamic Control System (DCS) [5,6,7], the Integrated Avionics Unit (IAU) and the command and data handling flight software (C&DH FSW). The DRS was closely coupled with the gravitational sensor provided by ESA on LPF. Drag-free spacecraft control implies a spacecraft trajectory that is affected only by external gravitational forces acting on test masses, to the extent possible, and not by other disturbances such as solar pressure or the spacecraft itself. Precision spacecraft control was needed to reduce noise forces from the spacecraft on the test mass. The GRS consisted of two freely floating test masses within a housing and a measurement system for determining the position of the test masses with respect to the housing and each other. In order to validate the performance of a gravitational sensor, the motion of one of the test masses must be compared to a reference trajectory provided by the other. Both test masses reside in the LTP payload and are controlled by the DRS during periods of joint operation. The concept is illustrated in Figure 2. The time variation of the separation of the two test masses was used to determine whether external forces had been reduced to the required level necessary to enable future gravitational wave measurement missions.

Nanometer spacecraft position control was achieved by precisely measuring the position of the spacecraft with respect to a reference test mass and actuating multiple thrusters to maintain the spacecraft trajectory following the reference test mass. The test masses were intended to follow purely gravitational trajectories. In the absence of a

shielding spacecraft, the test mass trajectories would be affected by solar radiation pressure in addition to other forces. The spacecraft shielded the test masses from external forces but also created small disturbances of its own that had to be characterized as part of LPF. In the absence of a control system, solar radiation pressure would tend to push the spacecraft towards the test masses. In the steady state, the thrusters fired to exert the same force as the solar radiation pressure (plus other disturbance forces). The first use of this type of spacecraft position control was in Earth orbit, where the primary non-gravitational force was atmospheric drag, leading to the terminology for ‘drag-free’ control. For DRS, a multimode drag-free controller examined the attitude of the spacecraft and the position and attitude of the test masses provided by the LTP sensor to calculate applied forces and torques to the LPF spacecraft and LTP test masses. The LTP included the inertial sensor and optical metrology subsystems. LPF also included the Drag-Free and Attitude Control System (DFACS). DFACS controlled the spacecraft dynamics with sensors and actuators that include the inertial sensor and optical metrology sub-systems in the LTP, star-trackers and cold gas thrusters. The performance of the LPF with cold gas thrusters was measured to be $5.2 \pm 0.1 \text{ fms-2}/\sqrt{\text{Hz}}$ for frequencies between 0.7 and 20 mHz [3]. This value is lower than the requirement for the LPF mission by 5x and within a factor of 1.25 of the requirement requirement for the LISA mission [3]. In the DRS, the spacecraft position was adjusted by colloid microthrusters with submicronewton level precision.

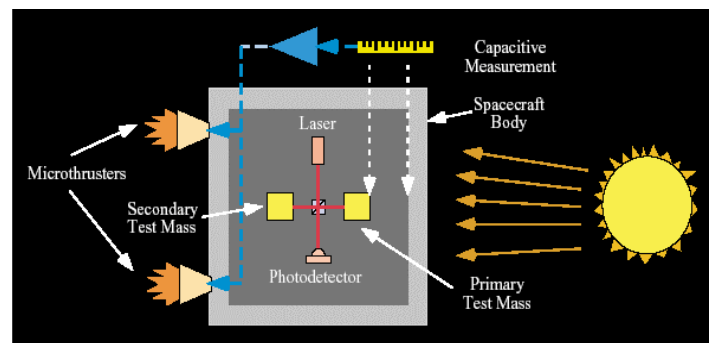


Figure 2. An illustration of the DRS concept.

The ST7-DRS technology demonstration mission had the following technology validation requirements, which constituted the project objectives:

- DRS shall demonstrate spacecraft control with $10 \text{ nm}/\sqrt{\text{Hz}}$ over a frequency range of 1 mHz to 30 mHz.
- DRS shall use the LTP as its drag-free sensor
- DRS shall demonstrate a spacecraft propulsion system with noise less than $0.1 \mu\text{m}/\sqrt{\text{Hz}}$ over a frequency range of 1 mHz to 30 mHz
- DRS shall operate with two clusters of four thrusters each to control the spacecraft attitude for at least 60 days. An assessment of the operability of the thrusters during the period will be made including: delivered thrust, specific impulse, latencies, warm-up times, controllability, throttleability, and accuracy. This requirement was changed before launch after the propulsion system was delivered and integrated onto the spacecraft more than 6 years before the launch. The requirement was changed to be met if any measureable thrust was produced on-orbit.

The ST7-DRS was successful at meeting all of the project objectives during the primary mission. It demonstrated attitude and drag-free spacecraft control, including transitions between different modes using the CMNT and the DCS for the first time in flight. Eleven experiments were conducted on the DRS over the 6 month primary mission. During four weeks of an extended mission, fifteen more experiments were conducted. The experiments were focused on demonstrating, characterizing and improving the drag free control, thruster performance and the thruster performance model. The performance of the DRS DCS in flight in meeting the ACS and drag-free requirements on position and acceleration noise have been summarized previously [5,6,7]. This paper is focused on presenting the performance of the colloid micronewton thruster system. The configuration and operation of the DRS and the different control modes are described. The performance of the CMNT system is summarized.

II. ST7-DRS

The Disturbance Reduction System (DRS) consisted of four major subsystems in three units. The four subsystems included the colloid micronewton thrusters (CMNT), Dynamic Control System (DCS), the Integrated Avionics unit (IAU) and the command and data handling flight software (C&DH FSW). They were integrated into 3 units that included the Electronics Assembly (EA) and two identical Colloid Micronewton Thruster Assemblies (CMTAs), also referred to as clusters. The Electronics Assembly consisted of the Integrated Avionics Unit (IAU) and a connector panel. The two thruster assemblies contained four microthrusters each and their corresponding electronics. An exploded view of the LISA Pathfinder spacecraft with the ST7-DRS payload is in Figure 3. DRS was a unique payload in that during operations, it controlled the spacecraft attitude and another payload, the LISA Technology Package (LTP).

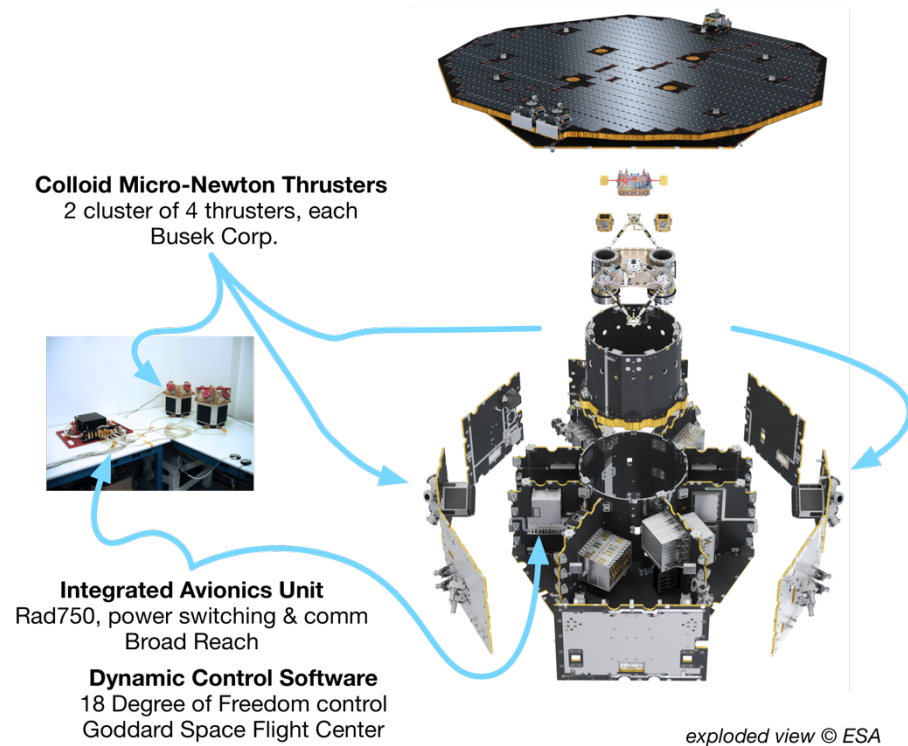


Figure 3. Exploded view of the LISA Pathfinder spacecraft with the ST7-DRS payload.

The DRS was powered by the LPF spacecraft power management system and communicated to the spacecraft on-board computer (OBC) via serial communications connection. The DRS could be controlled by the LPF to provide a backup thruster function or control the spacecraft attitude and LTP test masses during the DRS demonstration through commands and telemetry exchanged with the OBC. The OBC on-board software (OBSW) and on-board data handling (OBDH) provided the DRS interface software and data handling. Figure 3 shows the units and assemblies of the DRS instrument. The LPF OBC, LTP Front-End Electronics, and the two Test Masses are shown in the Figure 3 also, because although external to the DRS instrument, they were necessary to the DRS experiment as the gravitational reference sensors.

A. CMNT System

The two Colloid Micronewton Thruster Assemblies (CMTAs) are identical units provided by Busek Co., Inc. A single unit with four thrusters is shown in Figure 3. A thruster assembly included: 4 thruster heads, 4 propellant feed systems, 4 Power Processing Units (PPUs), 1 cathode, and 1 Digital Control Interface Unit (DCIU) [4]. The thruster head and feed systems were independently controlled through the PPUs, which were controlled, in turn by the DCIU. The DCIU had a power, command, and telemetry interface to the IAU. The DCIU also controlled the cathode neutralizer. The DCIU had an on-board PROM that stored thruster operating software and control

algorithms, which could not be reprogrammed after delivery to JPL. Each thruster head included a manifold that fed nine emitters in parallel, a heater to control propellant temperature and physical properties, and electrodes that extract and accelerate EMI Im ionic liquid propellant as charged droplets. The thrust from each head was throttleable from 5 to 30 μN by changing the beam voltage (2-10 kV) and/or the propellant flow rate that determined the beam current (2.25-5.4 μA). A thruster electrical schematic is shown in Figure 4. Independent, fine control of both the beam voltage and beam current allow for precise control of thrust to better than 0.1 μN resolution with $<0.1 \mu\text{N}/\sqrt{\text{Hz}}$ thrust noise. Propellant was stored in four electrically isolated stainless steel bellows compressed by four constant force springs set to supply four microvalves with propellant at approximately 1 atm of pressure. The CMNT functional block diagram is shown in Figure 5. The microvalve was piezo-actuated using $\sim 1 \text{ mW}$ of power to control the propellant flow rate and current to better than 1 nA without significant motion. This level of precision corresponds to a thrust resolution of $\leq 0.01 \mu\text{N}$, with a response time over its full range of less than 0.5 s [8].

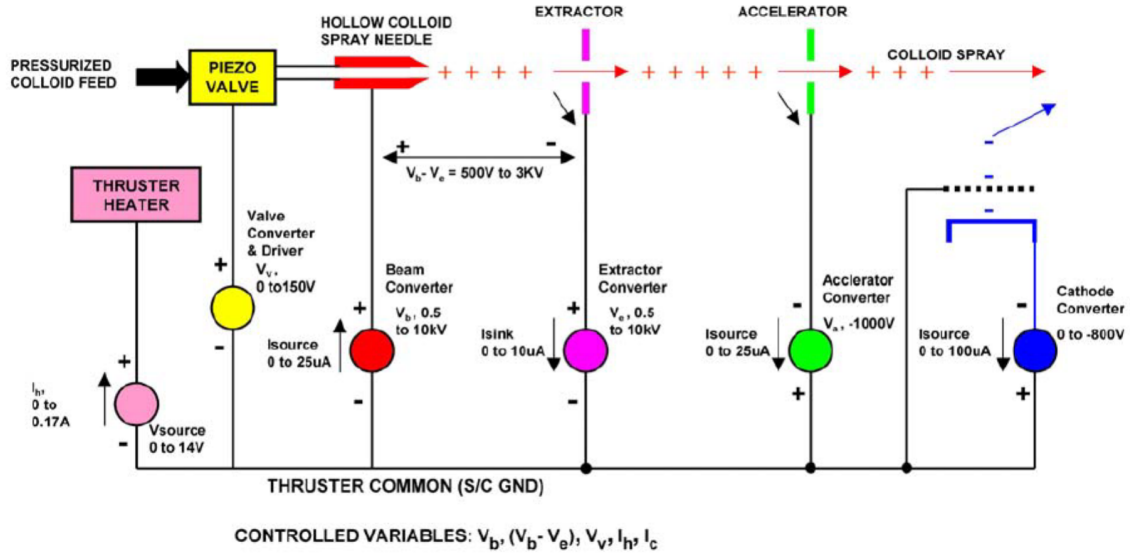


Figure 4. Thruster electrical schematic showing beam, emitter, extractor, accelerator, and cathode neutralizer voltage sources [9].

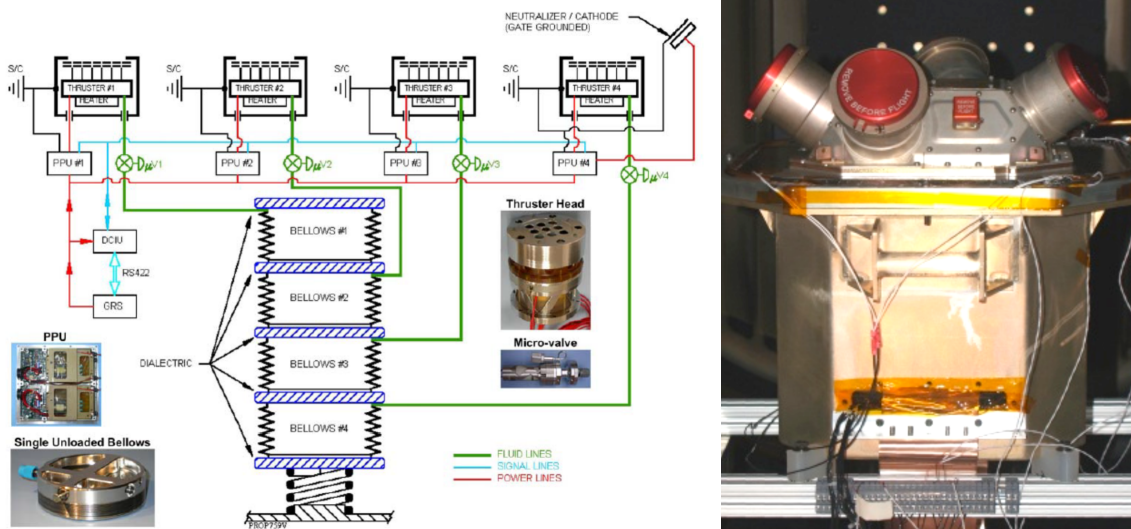


Figure 5. CMNT cluster functional block diagram [9] with pictures of various components (left) and the Busek Colloid Micro-Newton Thruster (CMNT) Flight Cluster 1 including four thruster heads, electronics, and cathode neutralizer (visible) in thermal-vacuum environmental test setup (right).

The thruster performance is based on ground tests of Engineering Model (EM) units on a thrust stand, which have been used to calibrate performance models based on current and voltage measurements. Those performance

models were used to verify that the flight units met requirements since they were too heavy to be placed on a thrust stand themselves. A lifestest was conducted with an EM unit thruster for 3478 hours. Performance measurements were conducted separately on a magnetically levitated thrust stand with micronewton resolution [10]. The simple model for thrust (T) in Equation 1 is based on beam current (I_B) and beam voltage (V_B) measurements and was developed and verified during ground testing with the thrust stand. The delivered thrust was achieved within 2% of the commanded thrust at nominal voltages, currents and temperature, which was within the resolution of the thrust stand, and with a C_1 of 0.0319. The nominal temperature is 25°C. The nominal beam voltage is 6000 V. The nominal extraction voltage is 1600 V. The nominal current range is 2.25 – 5.3 μ A. At non-nominal voltages, Taylor one losses and beam divergence effects can impact the thrust, by <2% for beam voltages between 4-8 kV and <5% for the full range of typically allowable beam voltages (2-10 kV). Temperature also influences the value of C_1 , which increases at colder temperatures and decreases at warmer temperatures. The exact relation between C_1 and temperature has been predicted using models including the physical properties of the propellant and verified by measurement [11].

$$T = C_1 I_B^{1.5} V_B^{0.5} \quad (1)$$

The propellantless field emission cathode neutralizer, developed by Busek, was fabricated from carbon nanotube (CNT) base with an opposing gate electrode. The cathode was capable of producing 10 μ A to 1 mA using extraction voltages of 250 to 800 V. One CNT cathode has been tested in an ultra-high vacuum chamber for over 13,000 hours at 100 μ A without incident. CNT cathodes have also been tested successfully with operating thruster heads during the pre- and post-dynamic tests and in each full functional test during the thermal environment qualification tests for each unit. Cluster 1 cathode demonstrated 13 μ A at 242 V and 23 μ A at 268 V in TVAC testing before flight. Cluster 2 cathode demonstrated 13 μ A at 375 V and 26 μ A at 420 V.

The thruster electronics included 4 power processing units (PPUs) and one digital control and interface unit (DCIU) for each cluster. They completed qualification testing at the component level and in flight assembly qualification testing [12]. EM and flight electronics have over 10,000 hours of operation under vacuum controlling complete thruster sub-systems. The PPU includes the high-voltage DC-DC converters that have been specifically designed and tested for this application by Busek Co. The DCIU controls all four thrusters and provides the command and telemetry interface to the spacecraft and DRS flight computer.

B. DCS

The flight software implementing the DRS Dynamic Control System (DCS) algorithm resides in the IAU and was used to control the spacecraft and the test masses. It performed this function by computing thruster force commands to maintain spacecraft attitude and test mass force and torque commands for drag-free operation based on spacecraft attitude and test mass positions and attitudes received from the OBC [5,6,7]. Its functions included sensor processing (from LTP and LPF), control filters propagation, actuation command generation (Thrust commands and electrostatic actuation commands) and internal fault notification. The on-board data handling (OBDH) of the OBC interacts with the DRS C&DH software on the IAU to pass commands and telemetry back and forth. The OBC stores ground commands on the MTL and telemetry from the DRS.

There are several DRS and DCS modes with different internal subsystem states within each mode. The DRS instrument enters a certain mode when the subsystems take on unique states within each mode. Each subsystem state may be commanded independently. **Initialization/Safe Mode (Init or Safe)** is the mode the DRS instrument enters upon power being applied from the spacecraft. Only the IAU had power in this mode. This was also the instrument's Safe mode. **Standby Mode** was the mode in which the DRS was not controlling either the spacecraft or the LTP test masses, and its IAU and thrusters were on but disabled. Standby Mode was considered the initial mode for DRS operations. When the DRS thrusters are on and being commanded, they are commanded in one of two ways. In **Thruster Command Mode (ThrCmd)**, the thruster level of each thruster is directly commanded. **Thruster Diagnostic Mode (ThrDiag)**, as initially implemented is the mode in which the DRS is not controlling either the spacecraft or the LTP test masses, its IAU and thrusters are on and enabled (thruster DCIU is on, PPUs are enabled) into diagnostic mode. This allows the thrusters to operate based on current and voltage commands (each thruster can be commanded independently) or thrust commands from the IAU. This mode was only expected to be used during commissioning phases or thruster fault diagnosis and recovery activities, but after a PROM anomaly in the DCIU (See Section V), the mode implementation was adjusted to allow its use while the DRS was controlling the spacecraft, and then the mode was used for most of the rest of the mission.

When DRS is in control of the spacecraft, the DCS uses five control modes. **Attitude Only Control Mode (ATT)** stabilized the attitude of the spacecraft and the attitude and position of test masses after handover from the LPF without compensating for solar pressure. Both test masses were in high force (wide range) mode and the DCS test mass controllers were both in accel mode. Spacecraft attitude was controlled by the micro-newton thrusters.

Zero-G Mode (ZG) mode maintained spacecraft and test mass states while opposing solar pressure and other secular forces acting on the spacecraft using the micro-newton thrusters. Both test masses were either in high force (wide range) or low force (high precision) mode and the DCS test mass controllers were both in Accelerometer mode to operate the test masses as accelerometers. Spacecraft attitude was also controlled by the micro-newton thrusters. This mode was used to measure thruster thrust levels. **Drag-Free Low Force (DFLF)** established drag-free motion about the reference test mass using the micro-newton thrusters. The reference test mass transitioned into Low-Force (high resolution) mode, with no electrostatic force commanding, although small torque commands may have been used. In this mode the spacecraft was required to center around one test mass. **18 Degree-of-Freedom (18-DOF)** was the second drag-free mode and the highest control mode for the DRS, controlling all 18 degrees of freedom with the highest fidelity. This was the expected mode for “science” operations with the reference test mass freely floating and the spacecraft attitude stably controlled by the colloid thrusters. In this mode, drag free motion was to be maintained for two test masses along the sensitive axis and within the DRS bandwidth.

The DCS provided both attitude and drag free control with the required performance with the colloid thrusters. It was required to maintain the spacecraft Z axis to an absolute accuracy of 2 degrees (3 sigma) half cone angle with respect to the Sun vector and the rotation around the Z axis to an accuracy of 2 degrees (3 sigma) with respect to the steering law. It was required to maintain the spacecraft position with respect to the test masses, about the sensitive axis (x-axis of the LTP housing frames H1 or H2), to better than 10 nm/√Hz in the measurement bandwidth (MBW). The measurement bandwidth covers the frequency range of 1 mHz to 30 mHz. It was required to maintain the spacecraft position with respect to either test mass, about the H1Y (or H2Y), to better than $30(1+f/(3 \text{ mHz})^2) \text{ nm}/\sqrt{\text{Hz}}$ in the MBW. It was required to maintain the spacecraft position with respect to either test mass, about the H1Z (or H2Z), to better than $30(1+f/(3 \text{ mHz})^2) \text{ nm}/\sqrt{\text{Hz}}$ in the MBW. It was required to maintain the relative attitude of either test mass with respect to its housing about any axis, to better than $500(1+f/(3 \text{ mHz})^2) \text{ nrad}/\sqrt{\text{Hz}}$ in the MBW. The performance of the DRS in meeting all off these requirements is presented elsewhere [5] with this paper focusing on the performance of the CMNT thrusters.

III. CMNT Flight Performance

The performance of the CMNT were characterized during commissioning and primary and extended mission phases in different modes and experiments. The critical thruster performance demonstrated in flight is summarized in Table 1 with requirements and ground test results for comparison and then discussed in more detail in the sections that follow. The thrusters performed as expected and required in flight, as they did on the ground, except that Thruster 1 had a slower response time and higher noise level. Despite the compromised thruster 1 performance, the DRS system delivered the required performance.

Table 1. CMNT performance requirements and performance summary.

Performance Parameters	ST7 Requirement	Ground Tests	Demonstrated in Flight							
			Thr 1	Thr 2	Thr 3	Thr 4	Thr 5	Thr 6	Thr 7	Thr 8
Thrust Range (μN)	5 to 30	4.35 to 35.8	5-30	5-50	5-30	5-30	5-60	5-30	5-30	5-30
Thrust Precision (μN)	≤0.1	0.08 (0.01 calculated)	≤1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1
Thrust noise (μN/√Hz)	≤0.1	≤0.01 (3x10 ⁻⁵ to 3 Hz) <0.1 (3-4 Hz)	≤0.8	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1
Thrust Range Response Time (s)	≤ 100 s	< 10 s	147 s	<10 s	<10 s	<10 s	<10 s	<10 s	<10 s	<10 s
Operational Lifetime (hours)	any measurable thrust on-orbit*	3478 hours during FLT 2B (245 Ns of impulse, 113 g of propellant)	>2400 hrs (100 days)	>2400 hrs (100 days)	>2400 hrs (100 days)	1690 hrs, (70 days)	>2400 hrs (100 days)	>2400 hrs (100 days)	>2400 hrs (100 days)	>2400 hrs (100 days)
Propellant mass sprayed (grams)	none	113	74.8	67.02	84.1	68.89	64.46	59.05	91.07	89.52

* Given the unplanned 7+ years they sat, fully fueled after delivery. Goal was ≥2160 hours (90 days).

C. Thrust Range

The CMNT performance was verified in flight and was consistent with performance data from ground tests. The ground and flight performance are presented in Table 1. Commanded and calculated thrust levels are presented in Figure 6 for each of the 8 thrusters in the required 5-30 μN thrust range. The thrust levels are calculated from measured current and voltage and the thrust model in Eqn 1. Thruster 1 did demonstrate the full thrust range, however it required ≤ 147 s, instead of 10 s as demonstrated by the other thrusters. In the extended mission, higher than nominal thrust levels were explored to demonstrate the capability. Thrusters 2 and 5 were stepped up to 40 μN early in the extended mission and then they were stepped up to 50 and 60 μN in the last week of the extended mission. These data are in Figure 7.

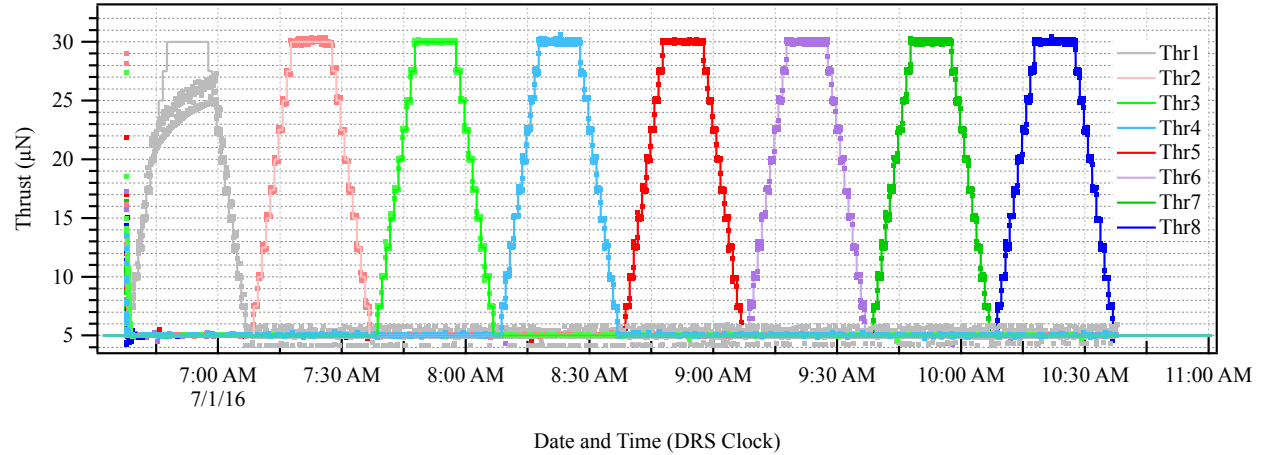


Figure 6. Commanded (solid lines) and delivered (dots) thrust for each of the 8 thrusters during a functional test to demonstrate 30 μN thrust range capability on one thruster at a time.

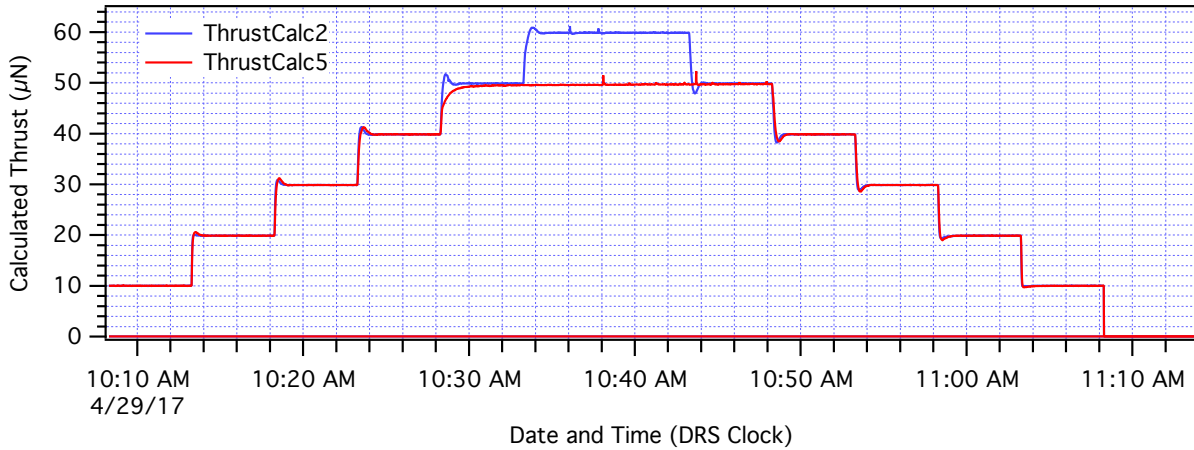


Figure 7. Higher thrust range demonstrated for thrusters 2 and 5 up to 50 and 60 μN .

D. Thrust Precision

The thrust precision met the 1σ requirement of 0.1 μN . Data in Figure 8 show the thrust precision control of thrusters 3 and 4. This precision was limited by the 12-bit A-D converter, and could have been improved with a 16-bit converter.

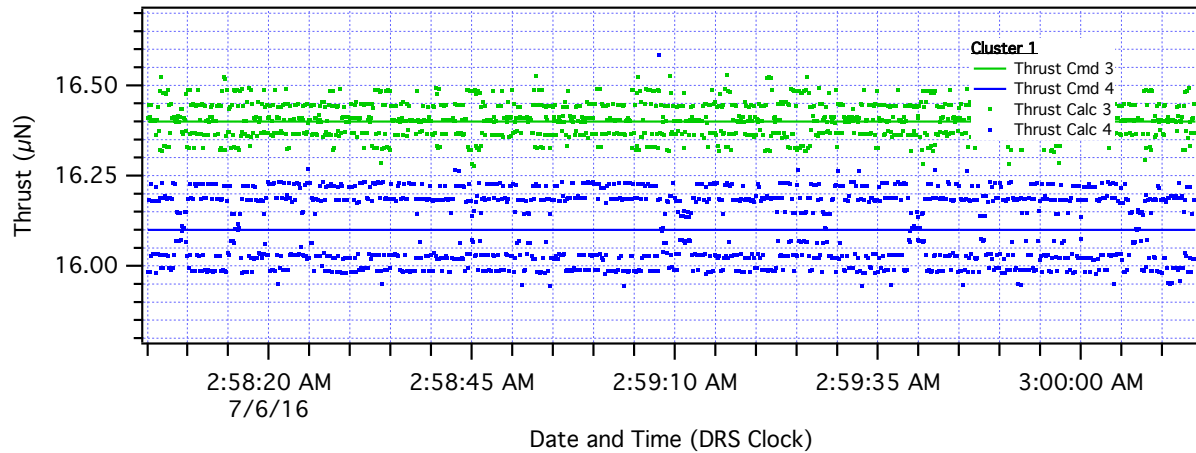


Figure 8. Data verifying required 0.1 μN thrust precision in Zero-G mode on DoY 188, July 6, 2016.

E. Thrust Response Time

The thruster response time met the requirement in stepping from 5 to 30 μN in ≤ 10 s, for all of the thrusters except for thruster 1. Thruster 1 did achieve the full thrust range in ≤ 147 s in multiple tests. Thruster response time data are presented in Figure 9 from the commissioning phase of the mission. Thruster 3 and 7 increased from 5 to 30 μN in 8 s. Thrusters 2, 4, 5, 6, 8 increased from 5 to 30 μN in 10 s. Initial thruster control algorithm parameters were selected based on achieving stable step changes over a wide range of initial operating conditions and thrust step magnitudes. It is anticipated that improved thruster response time may be possible through improved thruster algorithms and further optimization of control algorithm parameters.

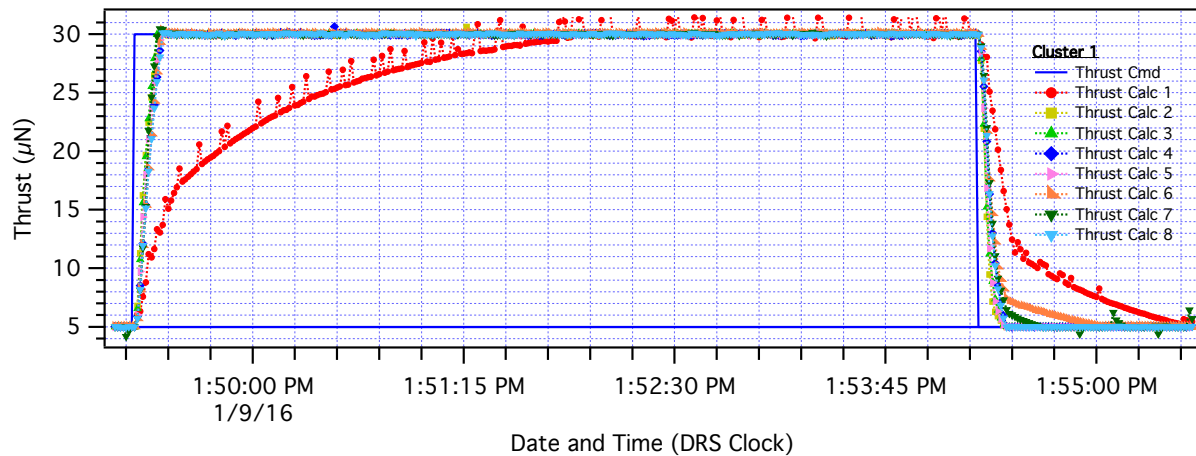


Figure 9. Data verifying thrust response time of ≤ 10 s for 5 to 30 μN , except for thruster 1 on DoY 008, Jan. 8, 2016.

The DRS was required to control both the spacecraft attitude and position in several modes. The thrust commands and the thrust delivered, as calculated using the measured thruster voltages and currents and the thrust model, are in Figure 9 for each of the modes for 10 minutes on DoY 276 for thruster 3. The attitude error limit of 2° (35 mrad) was maintained within the force and torque limits in all of the modes and transitions between them [5].

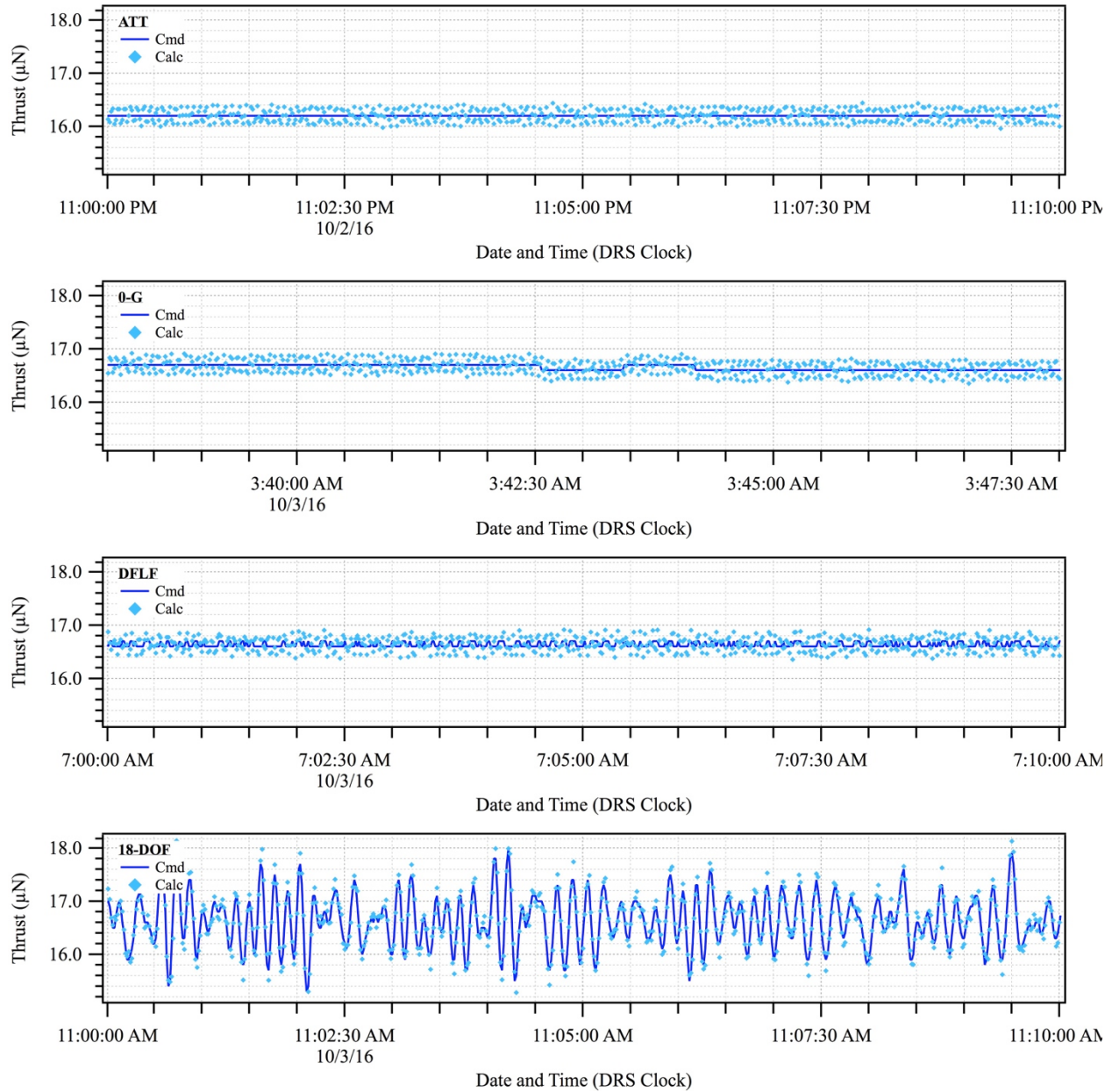


Figure 10. Commanded (solid dark blue line) vs calculated delivered thrust (lt. blue dots) in each mode (AC, ZG, DFLF, 18-DOF) for thruster 3 on DoY 277, Oct. 3, 2016.

F. Thruster Noise

The thruster noise requirement caps the average thruster disturbances within the DRS band. There are two top-level approaches to characterizing thruster noise on the spacecraft. The first is an open-loop characterization, which requires periods in which the thrusters operational, but not used in the control of the spacecraft, i.e., spacecraft is allowed to drift within the bounds of the Fault Management. The second approach involves characterization of thruster noise while the thrusters are used to provide actuation in the DCS controllers. This approach typically uses a pseudo-analytical model of thrust force to isolate thrust noise, and hence is model-dependent.

The open-loop characterization approach was chosen to verify the thruster noise requirement because it is direct and does not rely on a thrust model. Its use is further warranted since the thruster noise requirement applies to the CMNT subsystem, and is an average, per thruster, specification. A thruster experiment was conducted on DoY 245 (September 1, 2016), during which eight periods of free drifts were included. Prior to each drift period, the thrust

levels on the eight thrusters were fixed at their last values in order to compensate for secular forces and torques, and hence maximize the allowed duration of the drift. In each drift period, a sinusoidal thruster injection (at 23mHz) is included for 1 of 8 thrusters to characterize other aspects of that thruster like thrust precision and delays. This injection did not impact the noise characterization, as it is almost outside the band of interest, and it is narrow-banded. This experiment was performed with the DRS was in Zero-G mode, with the test masses as accelerometers.

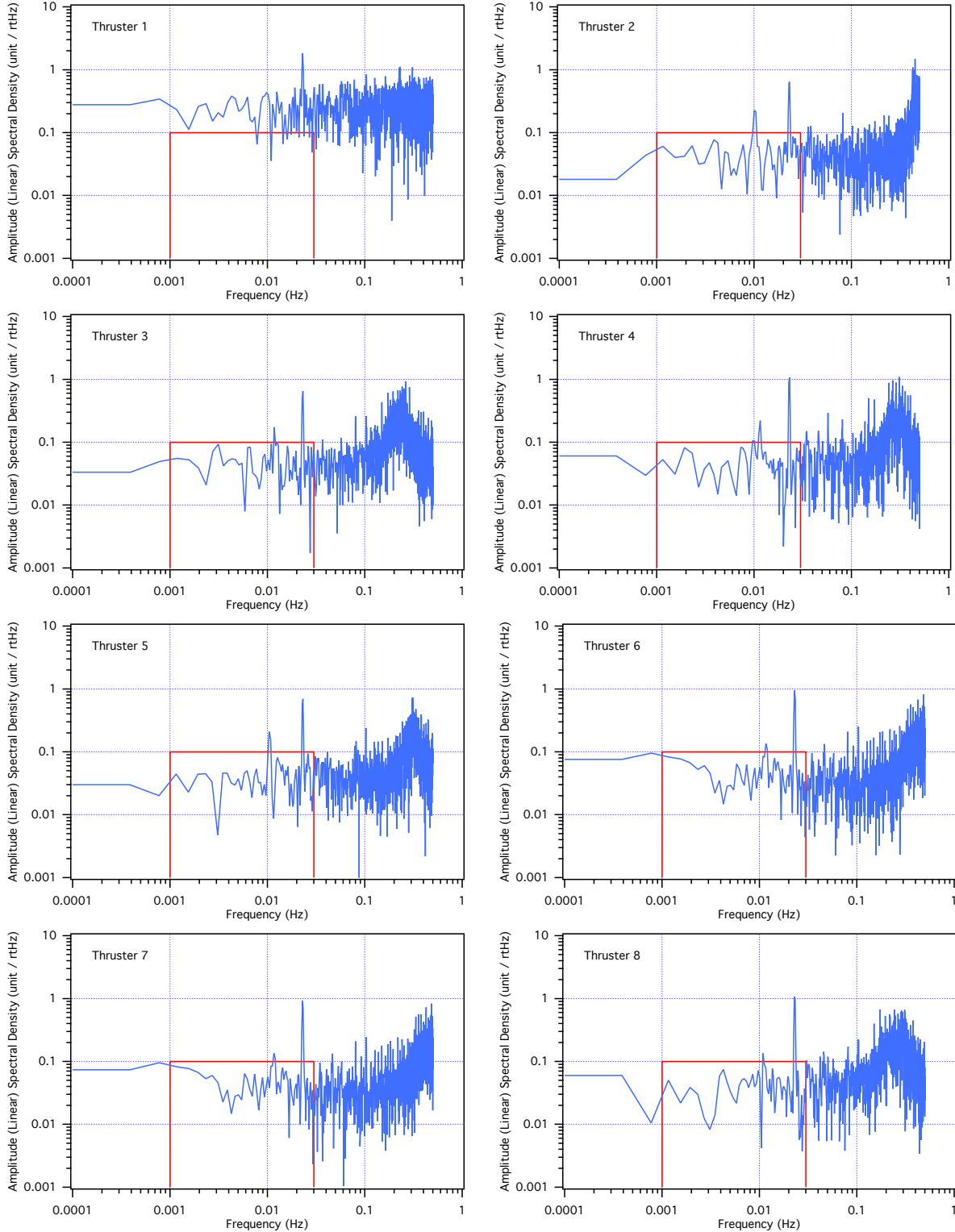


Figure 11. Thrust noise in DFLF on DoY 245, Sept. 1, 2016 over 2600 s with the requirement in red.

The thruster noise was characterized by calculating it for each thruster and then by measuring the collective thruster noise translated to the spacecraft. The individual thrust noise characterization is derived from the difference between the commanded thrust and the thrust calculated from the measured beam current and voltage using the thruster model. It is presented for the frequency range of interest for the LISA mission at 0.1 mHz – 0.1 Hz for each of the thrusters in Figure 11. The ST7-DRS thrust noise requirements was $\leq 0.1 \mu\text{N}/\sqrt{\text{Hz}}$ in the measurement bandwidth of 1 -30 mHz, as indicated by the red box. A thrust signal was injected at 23 mHz in the experiment, which introduced the signal peaks in noise amplitude spectral densities at 23 and 11.5 mHz. They are not attributable to thruster noise.

The spacecraft force noise was estimated by double differentiating the optical metrology system (OMS) data for each test mass along the sensitive axis (LPF data at 10Hz), subtracting the estimate of the applied ES force for each test mass, with appropriate scale factors (electrostatic force, ratio of spacecraft mass to mass of the test mass) and time delay, and finally averaging the force noise estimates from the two test masses. The amplitude spectral density of the spacecraft force noise, which is expected to be dominated by the colloidal thruster noise, averaged over the 8 thrusters, is shown and compared to the requirement in Figure 12. The average thrust noise meets the requirement with margin. The sharp peak at 23mHz is due to the thruster injection signal and should be ignored. The spacecraft force noise is cross checked by using the average estimates of the applied electrostatic force (adjusted for mass ratios and actuation scale factor) for the test masses. This cross check is limited to the effective bandwidth of the test mass Accelerometer mode in Zero-G (~4 mHz). The results are presented in Figure 12, where a good match is observed and were originally presented [5].

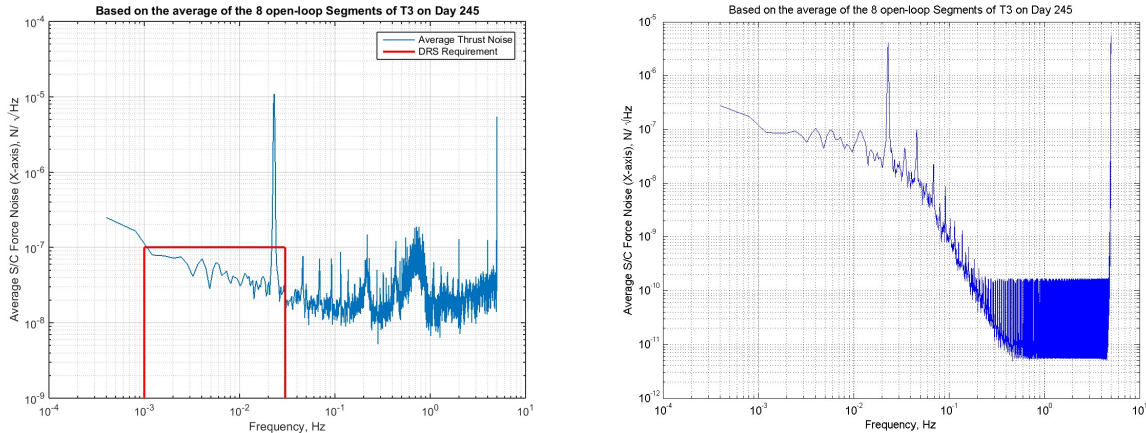


Figure 12. Amplitude spectral density of average thrust noise on the spacecraft. The red box shows DRS requirements, which are easily met. The graph on the right shows the amplitude of the average spacecraft force noise from electrostatic actuation commands only with the CNMTs off for comparison [5].

G. Thruster Response to Disturbance Event

During the primary mission several disturbance events were observed that were suspected as having been micrometeoroid impacts. The impact of the disturbance on the test mass position and angle and the control system and thruster response to successfully recover the spacecraft attitude, position and angle errors are presented in Figure 13. The DRS was responsive enough to manage the disturbances and maintain the required spacecraft attitude error. Several of these events were observed during the mission.

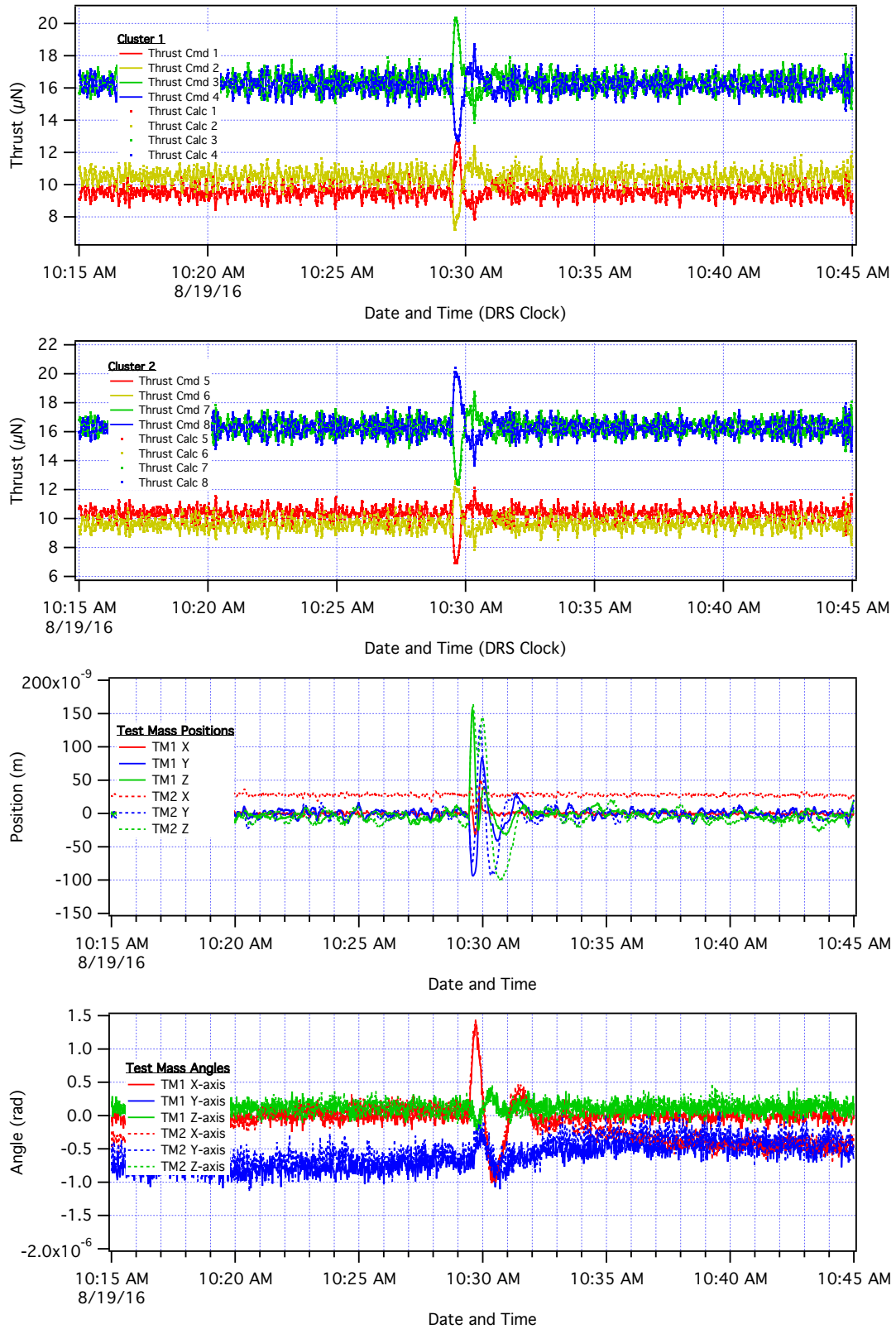


Figure 13. Response of all 8 thrusters and the test mass position and angle to an unknown disturbance event to stabilize the spacecraft attitude, position and angle on DoY 232, August 19, 2016.

IV. Carbon Nanotube Cathodes

The carbon nanotube cathode on each thruster cluster was tested in a thruster cluster current balancing mode. Each cluster with 4 thrusters has 1 carbon nanotube field emission cathode that is capable of emitting electrons at a current level that is equivalent to the combined current level of all of the thrusters in that cluster. Cathode data from the primary mission are in Figure 14. The graph shows the voltage, beam current, and current to the cathode gate electrode. The total thruster current for all thrusters in each cluster is also included in the graph. These data were sampled once per minute. The peak total current from each cathode was $\sim 14.8 \mu\text{A}$. The gate current was $\sim 4.9 \mu\text{A}$. The current escaping from the cathode, beam current, was $9.9 \mu\text{A}$. The beam current from each thruster was $2.5 \mu\text{A}$ and from each cluster was $10 \mu\text{A}$ at 12:07 pm. The cathode current balancing with the beam current was successful. Cathode 1 required 239 V. Cathode 2 required 473 V. This cathode test duration was about 16 minutes. The cathodes were tested again during the extended mission with 6 on-off cycles with independent control of cluster 1 and 2 cathodes. These data are in Figure 15. They show repeatable performance throughout the cycles. The cluster 1 cathode emitted $5.6 \mu\text{A}$ of beam current at 249 V and cluster 2 emitted $5.6 \mu\text{A}$ of beam current at 463 V. In TVAC tests, Cathode 1 required 243 V for $20 \mu\text{A}$ of total current with $12 \mu\text{A}$ of beam current escaping through the extractor. Cathode 2 required 372 V for $20 \mu\text{A}$ of total current and $12 \mu\text{A}$ of beam current in the TVAC tests.

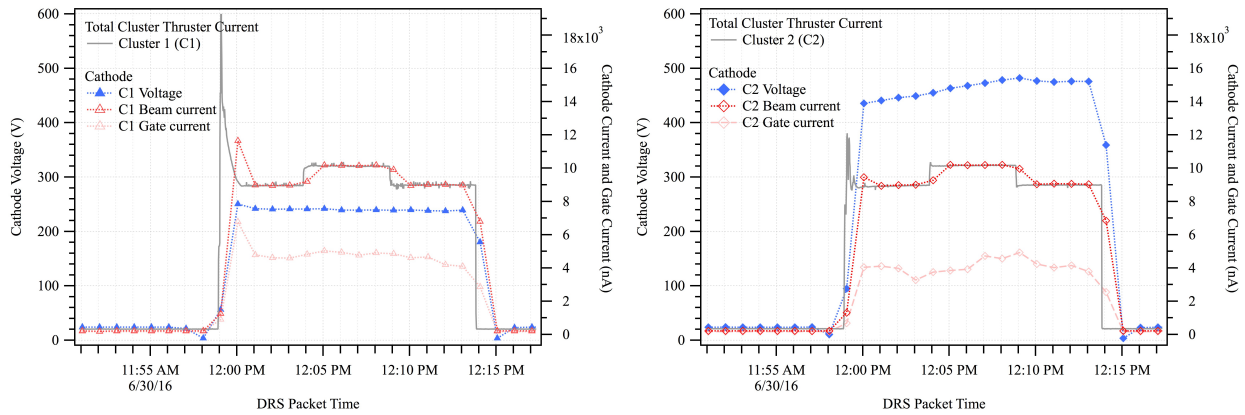


Figure 14. Cluster 1 (left) and Cluster 2 (right) cathode current and voltages while operating in a current balancing mode with the thruster clusters in the primary mission.

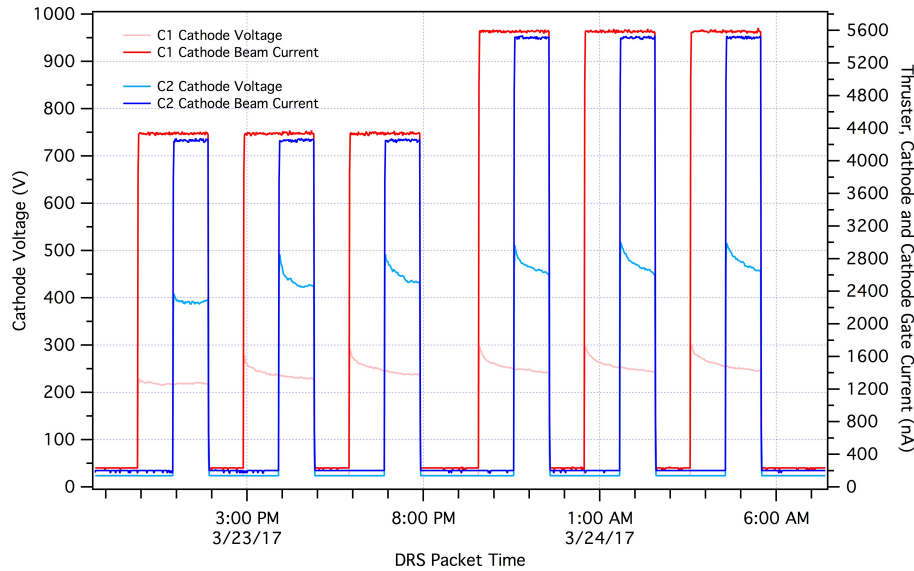


Figure 15. Cluster 1 (C1) and cluster 2 (C2) cathode beam current and voltages while operating in a current balancing mode with the thruster clusters in the extended mission for 6 cycles.

V. Anomalies

The DRS experienced 3 significant anomalies during the mission that affected operations; however, they did not prevent the mission from meeting the performance requirements. Thruster 1 demonstrated a delayed response time and a single intermittently operating emitter throughout the primary and extended mission that was not observed during TVAC testing before delivery and launch. The DCIU PROM suffered a partial memory failure in the location of the thruster control algorithm just after commissioning and at the beginning of the primary mission. Thruster 4 experienced a short between the emitter and the extractor electrode near the end of the primary mission during performance measurements beyond the nominal operating point. The anomalies were addressed and solutions were developed to enable operations to continue through the extended mission.

A. Thruster 1

Thruster 1 performance in flight was not consistent with the TVAC tests on the ground before delivery and launch. In the TVAC tests, the response time was 9.8 s to increase from minimum to maximum thrust of 5 to 30 μN , as required. In flight, this thruster took longer than the other thrusters to turn on and initially had a response time of about 147 s. The requirement was 100 s, although this response time requirement did not significantly impact DRS operations. The response time increased slightly during the mission, primarily for the first turn on after a prolonged period of being off. In flight, the beam current spikes were consistent with a single capillary emitter turning on and off ($\sim 0.25 \mu\text{A}$), was observed every few seconds, depending on the current level, throughout the entire mission, indicating that one emitter of the nine was turning on and off. This behavior was not observed during TVAC testing. The delayed response time and current spikes indicated a change in hydraulic resistance of the thruster and performance of the valve. Experiments were conducted in the extended mission to try to improve the response time and characterize the current blipping to determine if there was a bubble in the thruster or particulate contamination and if the delayed response was attributable to a valve piezo element failure. No cause has yet been determined for the increased microvalve response time. Particulate contamination in an emitter could have increased the hydraulic resistance to severely limit the flow rate and cause one of the emitters to blip on and off. Both of these performance changes were observed at the same time, suggesting that they could be related; however the location of the two issues is likely not the same. Because all of the other 7 valves performed the same in flight as on the ground, this anomaly may be a technology development yield issue that can be addressed by maturing the technology and/or flying redundant valves, as is common practice for science missions.

B. DCIU

The DCIU experienced an anomaly on July 8, 2017 that resulted in a processor reset and thruster cluster 2 being disabled when it received a thrust command. Testing revealed that while the Thrust Command Mode no longer functioned properly, the Diagnostic Mode and other control routines still functioned well. The thruster control algorithm then had to be executed in the FSW on board the IAU instead of the DCIU to prevent the reset as the DCIU PROM and software could not be changed on orbit. In this 'Diagnostic Mode' the FSW calculated the thruster current and voltages from the DCS thrust commands using the thruster control algorithm, instead of the DCIU, and then passed them through the DCIU to the PPU. An old version of the thruster control algorithm that was in the IAU FSW was modified as required, to enable this Diagnostic DCIU Pass-through Mode, and operations continued on August 8, 2016. The expected cause of this anomaly is a radiation event. While this work around solved the immediate issue, it also introduced a command and telemetry delay between thrust command processing and beam current and voltage commanding and execution. This added delay was 1 realtime interval (RTI), which resulted in additional thrust noise from beam voltage variations. A more robust and re-writable memory is recommended for future missions to prevent this type of anomaly. While this diagnostic mode approach created a timing delay in the control loop that resulted in noise on the beam voltage and increased thruster noise, the DRS met the noise requirements for the mission.

C. Thruster 4

Thruster 4 developed an effective electrical short (200 MOhm) between the emitter and extractor near the end of the primary mission that rendered it inoperable. The short was developed on Oct 27, 2016 after 1670 hours of operation. The exact location of the short cannot be determined without access to the thruster, but it was determined to be between the emitter and extractor electrodes. This electrically conductive bridge could have formed when the extractor collected enough propellant to spray back to the emitter and become polymerized by the current and high energy charged particles. This anomaly may be partially attributable to an abbreviated thruster shutdown procedure

that was adopted during station keeping maneuvers to shorten the procedure and preserve the spacecraft thermal environment at the request of ESA. The safe thruster shutdown procedure includes multiple steps to decrease the quantity of residual propellant in the emitters to reduce the risk of spraying during standby. Current flickering on and off at 0.05-0.25 μA level was observed, typically only from thruster 4, during these days as propellant was drawn out with voltage applied and electrosprayed. It seems likely that this flickering electrospray during the SKM contributed to the development of the propellant bridge, as this current could be sprayed between the emitter and extractor. This thruster also demonstrated more current flickering with the valve closed during TVAC testing before integration onto the spacecraft. It sprayed more charge in this flickering mode than any other of the thrusters. Determining how to prevent this current flickering will be critical to the further development of this thruster technology for future missions. Implementing redundant thruster heads will also be critical to future missions for the required lifetimes, as is common practice for science missions.

Because of the 8-thruster configuration and lack of authority around the primary x-axis with only seven thrusters operating, a hybrid “crutch” mode was developed to continue DRS operations using 4 of the LTP cold gas (CGAS) thrusters after the thruster 4 anomaly. The colloid thruster and cold gas thruster thrust bias levels as well as new handover procedures and sequences were developed also for this new operating mode. Both 4 and 2 CGAS thruster configuration were demonstrated on the test bed; however, the 4 thruster configuration was preferred to reduce the required colloid thruster thrust bias levels. This hybrid mode was demonstrated just before the last week of the primary mission in all DCS modes and continued successfully through the extended mission, with higher force noise than the purely colloid thruster mode, attributable to using the cold gas thrusters.

VI. Conclusion

The ST7-DRS payload on the LPF spacecraft successfully demonstrated two new technologies - Colloid Micro-Newton Thrusters (CMNTs) and a drag-free 18-degree-of-freedom dynamic control system (DCS), while meeting mission performance requirements to enable future gravity wave observatories. Together they demonstrated the required performance in spacecraft attitude, position and drag-free control, validating the DCS and CMNT and performance models. ST7-DRS also demonstrated the technologies that will be critical for future separated element interferometers and telescopes and other applications needing extremely low position noise. As a system, the electrospray microthrusters demonstrated the required performance in thrust range (5- 30 μN), precision (≤ 0.1 μN), response time ($< 100\text{s}$ for minimum to maximum and maximum to minimum thrust), noise (≤ 0.1 $\mu\text{N}/\text{rtHz}$), and operating time (60 days), consistent with ground test results. Two of the microthrusters also demonstrated 50 and 60 μN thrust ranges. The ST7-DRS demonstrated control stability during a significant disturbance events that were possibly micrometeoroid impacts. These colloid thrusters could provide even higher ranges of thrust by increasing the number of emitters in the head to accommodate various future mission applications and requirements. Significant thrust noise improvements, possibly by a factor of 10, are expected without the current blipping on thruster 1, by improving the thrust resolution with a 16 bit A-D converter and without the telemetry delay. The thruster response time could be decreased by changing the control algorithm parameters. Minor technology improvements are expected to the propulsion system including subsystem redundancy and propellant tank volume to achieve multi-year lifetime requirements for missions like gravitational wave and exoplanet observatories. Carbon nanotube cathodes were also demonstrated during commissioning and then again during the extended mission in a thruster current balancing mode through several cycles with stable and repeatable performance. This mission validated this electrospray thruster technology for spacecraft attitude and drag-free control for mission applications including gravitational wave observatories, like LISA.

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References

1. Ziemer, J. K., Romero-Wolf, A., Demmons, N., Hruby, V., "Initial Commissioning Activities for the Space Technology 7 Colloid Thrusters," IEEEAC-2233.
2. McNamara, P., et al., "LISA Pathfinder," *Classical Quantum Gravity*, 25, 114034 (2008).
3. Armano, M., et al. "Sub-Femto-g Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results," *Physical Review Letters* 116 231101 (2016).
4. Ziemer, J. K., Randolph, T. M., Franklin, G. W., Hruby, V., Spence, D., Demmons, N., Roy, T., Ehrbar, E., Zwahlen, J., Martin, R., Connolly, W., "Delivery of Colloid Micro-Newton Thrusters for the Space Technology 7 Mission," AIAA-2008-4826, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 21-23 July 2008, Hartford, CT.
5. Maghami, P. G., O'Donnell, J. R. Hsu, O. H., Ziemer, J. K., Dunn, C. E. "Drag-Free Performance of the ST7 Disturbance Reduction System Flight Experiment on the LISA Pathfinder," GNC 2017: 10th International ESA Conference on Guidance, Navigation and Control Systems, 29 May-2 June 2017, Salzburg, Austria
6. Hsu, O. C., et al, "Dynamic Control System Performance During Commissioning of the Space Technology 7 – Disturbance Reduction System Experiment on LISA Pathfinder," AAS 17-155, Proceedings of the AAS GN&C Conference, Breckenridge, CO, February 2017.
7. O'Donnell, Jr., J. R. Hsu, O., Maghami, P., "Dynamic Control System Mode Performance of the Space Technology-7 Disturbance Reduction System," 68th International Astronautical Congress, 25–29 September 2017, Adelaide, Australia.
8. Zwahlen, V. Hruby, V., Campbell, C., Demmons, N., Ehrbar, E., Freeman, C., Martin, R., Roy, T., Spence, D., "Flow control Micro-valve for the ST7-DRS Colloid Thruster," AIAA-2008-4930, 44th AIAA Joint Propulsion Conference, Hartford, CT, July 2008.
9. Hruby, V., et al, "Busek Colloid Thruster Development," *3rd Colloid Thruster Nano-Electrojet Workshop*, MIT, Boston, MA, April 14-15, 2005.
10. Ziemer, J. K. Randolph, T. M., Gamero-Castano, M. Hruby, V. Connolly, W. Demmons, N. Ehrbar, E., Martin, R. Roy, T., "Flight Hardware Development of Colloid Microthruster Technology for the Space Technology 7 and LISA Mission," IEPC 2007-288, 30th International Electric Propulsion Conference, Florence, Italy, September 17-20, 2007.
11. N. Demmons, et. al., "ST7-DRS Mission Colloid Thruster Development," AIAA-2008-4823, 44th AIAA Joint Propulsion Conference, Hartford, CT, July 2008.